FFR 120
Simulation of bug infestation

David Tonderski,* Ruxin Zhou,† and Joakim Svensson‡
Chalmers University of Technology
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The spread of invasive insects can have an adverse impact on peoples' property and health. Due to the strong vitality and quick reproduction of these species, there is still no effective method to reliably control bug infestation. To provide a qualitative and quantitative analysis, this project creates a framework for realistic simulation of German cockroaches infesting a house. Through the use of object-oriented programming in MATLAB, an agent-based model is created to let bugs and humans act individually and probabilistically in a house with realistic parameters. The evaluation shows that the model behaves as expected and is reasonable. Based on the main model, a bug control technique has been integrated and its effect and threshold have been evaluated. In summary, the lack of real-world data makes it hard to prove or disprove the model's realism, but the analysis that was done shows that at least a groundwork for a realistic model has been created.

I. INTRODUCTION

A. Background

Insects are the most diverse type of creatures on the planet, representing over half of all known living organisms[1]. Insects are critical for the ecosystems to function all across the globe and are essential for humans to survive. However, there are some species that could cause harm to humans and damage to property. These types of insects are called invasive insects.

Invasive insects such as bugs, cockroaches and termites can lead to massive damage if they are allowed to spread freely. They can eat through walls and destroy property like clothes and furniture. Some of them can also be dangerous to humans; for example they can spread diseases like salmonella through biting[2].

B. Motivation

Invasive insects can be very difficult to control due to their resistance to pest control methods and their ability to adjust to the environment[3]. Even for pest control professionals, it can take months to eradicate invasive insects in a building.

The cost of damaged goods worldwide due to invasive insects is at least 70 billion US-dollars per year. Furthermore, worldwide problems related to human health caused by invasive insects cost almost 7 billion US-dollars per year[4].

To understand the complexity of bug control of invasive insects and to prevent the harm that they may cause to both constructions and humans, there is a need for a further understanding of their behaviour. By creating a realistic simulation of an environment where invasive insects can interact with humans, new or improved versions of bug control methods can be found.

Previously there has been no work done in this area and no articles about the type of simulation that this project is aiming to create were found. This project is therefore motivated by the need to investigate the behaviour of invasive insects and methods to prevent bug infestation.

C. Purpose

The project goal is to create a realistic bug infestation model in an enclosed environment. This model should lead to a better understanding of how invasive insects act. Ideally, the model should be possible to use in real-world situations to test various pest control methods.

II. METHOD

A model was created for simulation of bug control in an environment represented as an apartment. The model was built in MATLAB with the use of object-oriented programming which resulted in several different classes and methods that will be explained further on in this chapter.

Before any further explanation of the model it is important to know that it is only a specific species, the Blattella Germanic, also known as the German cockroach, that is considered in this project. The reason for choosing this bug is that it is fairly common in Europe and highly resistant to pest control methods.

A. Model structure

The model is based on a loop with interacting sets of objects. Each step of the loop corresponds to a real-world

* davton@student.chalmers.se
† ruxin@student.chalmers.se
‡ joaks@student.chalmers.se

time step of about 10 minutes, which is important, as the behaviour of the objects needs to be adapted to the time step length. The way the objects interact with each other is visualised in the class diagram in figure 1.

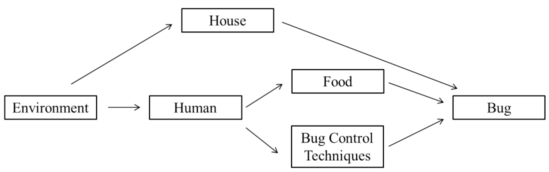

FIG. 1: The class diagram of bug infestation model.

The various classes are explained in more detail below.

a. Human represents the residents of the house. Because of the complexity of the human behaviour, it is explained in detail in section II B.

b. Bug represents the bugs. Similarly, their behaviour is explained in detail in section II C.

c. House is an enclosed environment wherein the bugs and humans are able to move around. It is based on walls, doors, and several different rooms: two bedrooms, a living area, a hallway, a toilet, a kitchen, and a closet. It also includes an location representing the area outside of the house which the humans are able to reach but the bugs cannot. Importantly, it is very simple to edit the house layout and run the model.

d. Environment is used to control the current time as well as the day-night and the weekday-weekend cycles.

e. Food controls the position and quantity of food in the house. Food can only be added by human littering and be removed by human cleaning or by bug eating. Eating food is the only way for bugs to reduce the hunger (see section II C). One unit of food is able to provide one day of energy for one adult bug.

f. Bug Control Techniques are the methods that the user can use to try to exterminate the bugs. The one implemented and analyzed in this project is pesticide. It is explained in more detail in section II D.

To visualise the model during the process a plot was created as shown in figure 2. At first the plot only consisted of walls which created the house, but as the model developed more features were added to the plot. The plot was made to confirm visually that the different objects worked as intended, for example that the bugs and humans were moving around in the house as they should.

B. Human behaviour

The goal of the human model is to simulate a person's behaviour during a day. This is done both stochastically with random movement and activities but also deterministically with certain activities that are repeated each day. It should be noted that in the simulation there are always two humans living in the house. They perform their activities separately and do not interact with each other in any way.

To begin with, the most important assumption is that the only activity of the humans that affects the bugs is cleaning. Therefore, no other tasks that the humans would perform in the real world are actually simulated. Another assumption is that each human has a job and goes to work each day between Monday and Friday. Furthermore the humans sleep at a regular time pattern between 12am and 8am. A brief overview of the human behaviour can be seen in figure 3.

At the beginning of each day, the humans sleep for eight hours. Then, they wake up, go to the kitchen to eat breakfast for one hour and go to work until 5pm. When the humans come home from work, they perform random activities until 12am and then they go to sleep.

These activities only determine the movement of the humans, so one activity could for example be staying in the living area for two hours. Each activity is performed for a certain time period, which means that when the humans finish their current activity, they go on to do the next random activity. Each activity has a certain probability of happening. For example, there is a larger probability that the humans go to the living area rather than the toilet.

As mentioned earlier, cleaning is the only task that affects anything other than the human's position. Cleaning a room means entering it and removing all of the food in it. The room to be cleaned is determined by roulette-wheel selection, which means that the room with the highest amount of food will most likely be selected.

Other than cleaning, the most important feature of the human behaviour is generating food. At every time step, each human has a probability of dropping food in the room that it is currently in. This probability is highest in the kitchen, because that is where humans usually eat. Eventually, the food that is not cleaned up will be the food that the bugs eat.

During the weekend, the behaviour of the humans is slightly different. To start with, there is no cleaning or working during the weekend. However, the probability that a human leaves the apartment is slightly larger than the probability of leaving the house on spare hours during the weekdays. This means that the humans will on average spend a similar portion of the day at home during the weekdays and the weekend. The feature that the humans change behaviour on the weekend was implemented to make the model more realistic.

C. Bug behaviour

An agent-based model is used to simulate the behaviour of bugs. The life cycle, reproduction, movement, diet and death are the five main aspects that the simulation focuses on.

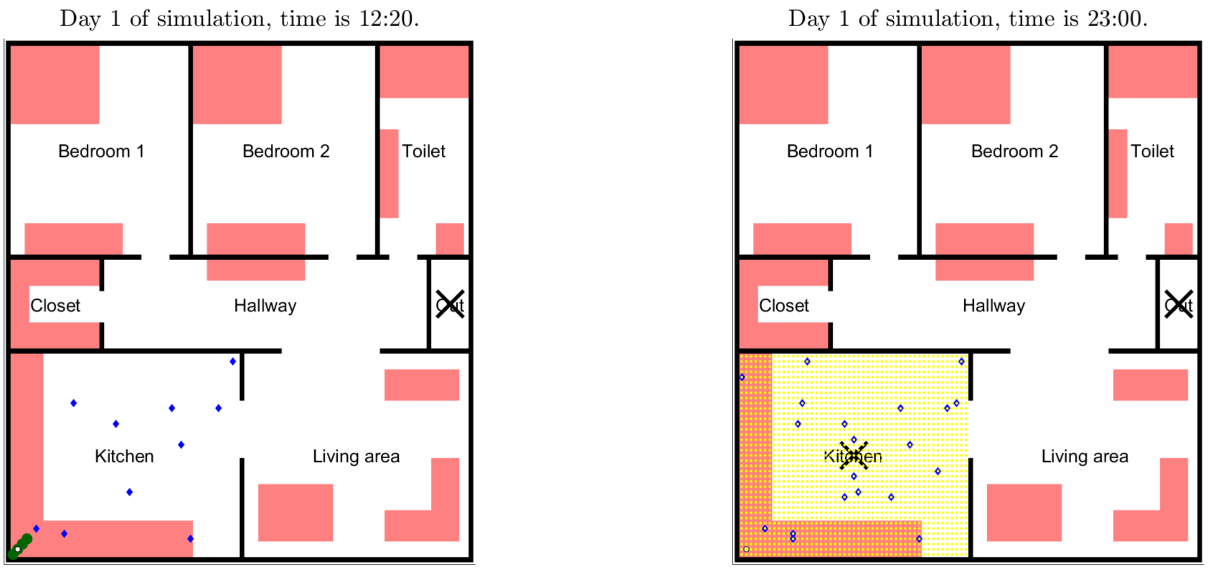

FIG. 2: Visualisation of the house as two plots in MATLAB. In the title of the plots the current day and time step are shown. In both plots, the house is visualised with walls and rooms represented by thick black lines. The black crosses in the plots are the humans, who in the shown time steps are in the kitchen or outside the house. The blue diamonds that are present in the kitchen are the food crumbs generated by the humans. The green circles are the bugs and the small white circles are the eggs. Note that the bugs and the eggs are inside the red areas, which represent the hiding places inside the house. The yellow circles mark the pesticide. As expected, the bugs have died when exposed to pesticide and therefore they are not present in the plot with pesticide.

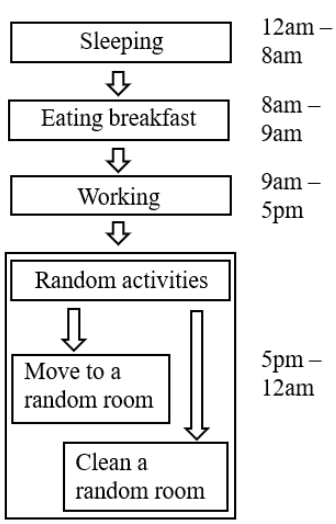

FIG. 3: A brief overview of the human behaviour during a weekday. The algorithm for random activities is shown in the form of a pseudo code in the lower part of the figure.

Life cycle: The life cycle of a German cockroach can be divided into three periods: egg, nymph and adult, with a total lifespan of 100-200 days. It takes 15-30 days for an egg to be hatched and become a nymph, 40-80 days for a nymph to grow to an adult, and 7 days for a new adult to be able to reproduce[5].

Reproduction: Once fertilized, a female German cockroach develops 2-3 oothecae in her abdomen, with 30-40 eggs per ootheca. After the first reproduction, a female is able to reproduce one or two more times even without a male cockroach[6][7]. To simplify the model, several assumptions are made. In the model, the definition of ootheca is ignored, and the number of eggs a bug can lay during one reproduction period is a random integer between 30 and 120. The interval between two reproductions is at least 30 days. Bugs can only lay eggs in hiding places, which are the only safe zone for them. Considering that a German cockroach has the same probability of becoming a male or a female, it is equivalent to assume that all of the bugs are able to reproduce but only half of the eggs are able to grow to nymphs.

Diet: The model assumes that the energy of a bug is continuously decreasing with a constant speed (i.e. 1 unit at each time step) and that a bug can only eat food littered by the human to obtain energy. The extent of hunger plays a significant role in the movement, reproduction and even death of a bug. The diet influences the life of a bug based on the following assumptions: if the time period that an adult does not eat food is longer than one month, the bug dies. Considering that the vitality is related to the life stage and the age, a newly-hatched nymph can only live for one week without food. Additionally, there is a linear relationship between the longest time period that a nymph does not eat food and its age.

The reproduction is also affected so that if a reproductive adult does not eat food for continuous two weeks, it cannot reproduce. In addition, the moving pattern of a bug is also influenced by the extent of hunger. In brief, the probability of a bug moving increases proportionally to its hunger.

Death: Under the following four conditions, a bug dies. First, it completes the whole life cycle and is old enough to die. Second, it is in the same room with the human and the human notices and kills it. Third, as described above, if a bug does not eat any food for a long time period, it dies of hunger. The fourth reason is due to the pesticide.

Movement: Considering the fact that the German cockroach cannot fly and is nocturnal[8], the movement area of bugs is limited to the floor and the movement frequency is much higher at night.

The movement of a bug is based on two assumptions. First, a bug moves to seek gains and avoid harm. The gains include the food and the hiding places, while the harm is the human noticing and human killing.

Thus, the movement of the bugs follow a specific rule. In priority, a bug tends to stay still or move around in the current room. The bug has a small probability of changing rooms under any conditions, but usually this only happens when there is no food in the current room.

The movement in the current room is divided into the following two patterns based on the current position of a bug. On the one hand, if a bug is in a hiding place, it usually stays still to avoid humans. If there is no human in the room, it has a certain probability to move out from the hiding place to search for food. On the other hand, if a bug is not in a hiding place, it will in the first place move to the hiding place and in the second place search for food if there is no hiding place in the current room.

The second assumption is that all the movement is probabilistic, and the probability is based on the human activity and the extent of hunger of bug itself. According to the construction of the human model, a human is more active in the day and less active at night. Thus, all the probability that is mentioned in bug movement is larger at night. Furthermore, the activity of a bug is linearly related to the extent of hunger. Bugs are more likely to move when they are very hungry. The basic pattern of bug movement is shown in figure 4. However, in extremity, if a bug will die in one day without any food, it ignores the human activity, and moves following the rule that the bug must move to seek food in the current room. If the current room has no food, it will move to another room to search for food.

D. Bug Control Method

Pesticide: Using pesticide to combat the bug infestation is based on several assumptions: first, the pesticide can be sprayed by a human when it is in the house and is not asleep. Second, at each time step, a human has a certain probability to spray pesticide in a specific room. The probability has a linear relationship with the times a human noticed a bug in the house. The room to be sprayed with pesticide is determined by roulette-wheel selection, which means that the room where a human has noticed more bugs is more likely to be selected. Once the human sprays the pesticide, the number of bugs it noticed in the room is cleared. Third, once a human sprays pesticide in the room, not all the coordinate points in the room are covered: hiding places are covered with a certain percentage. The covering time is limited to one time step. After that, the pesticide is removed. Fourth, considering that the bug should be resistant to drug to some extent, if the bug has been sprayed with pesticide, there is an 80% probability of death.

III. RESULTS AND DISCUSSION

A. Basic Model Evaluation

At first, the basic model without bug control measures was evaluated. This evaluation was split into two parts. To begin with, the simulation was visualised, and the model parameters were tweaked until the simulation reached a satisfactory level. Because of the lack of data about real-world bug movement and behaviour, this was not a quantitative analysis, but rather a qualitative one.

A more quantitative analysis was achieved by analyzing data from long simulations of about 100,000 time steps, or two years in the real world. First of all, a heatmap of bug positions was created to check whether the bugs were mainly located in the hiding places of the kitchen, where most of the food was generated. This is shown in figure 5. From the heatmap, it is clear that the bugs spent most of the time in the hiding places, as expected. Interestingly, the heatmap shows that the bugs are in the toilet, closet and bedrooms as much as in the kitchen, even though the probability of dropping food is only half of the kitchen's probability. This is most likely because the probability of cleaning a room is proportional to the amount of food in that room, so more food is generated in the kitchen, but it is also cleaned more frequently. Therefore, on average, there should be about as much food in the kitchen as in the toilet.

So the bugs overall move as expected, mostly staying in hiding places in rooms with food. Next, the ability of the bugs to find food to eat is evaluated. To do that, the mean number of adult bugs was plotted against the mean amount of food available to the bugs each night in figure 6. The data is then fitted to an exponential model

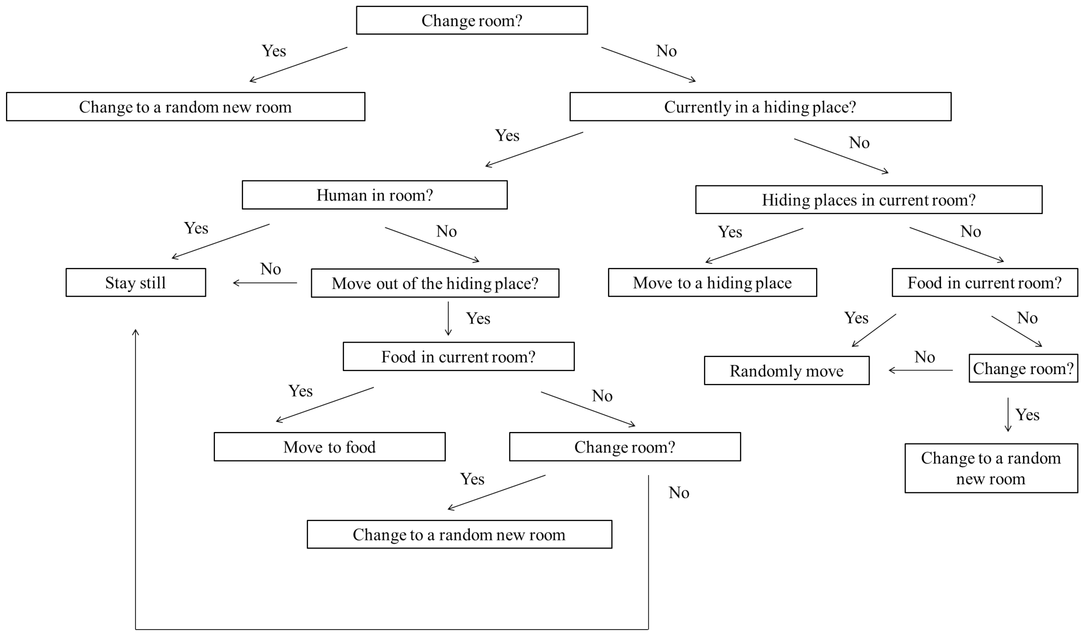

FIG. 4: The flow chart that shows the regular movement pattern of the bug. The movement rule followed by an extremely hungry bug is different.

with the result $y \approx 0.51x^{0.97}$. First of all, the exponent 0.97 implies that there is an almost perfectly linear relation, which is expected, as increasing the amount of food should reasonably increase the number of bugs proportionally. Then there is the coefficient 0.51. At first glance this looks strange; is only half the food used by the bugs?

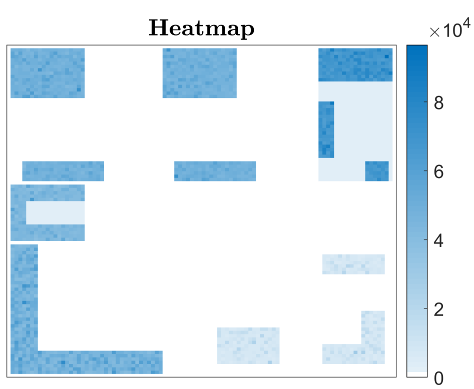

FIG. 5: Heatmap of the bug positions throughout a simulation of about 100,000 time steps. The data is calculated by adding 1 to a position for each bug on that position for each time step. Darker places mean that the bugs can more frequently be found in them.

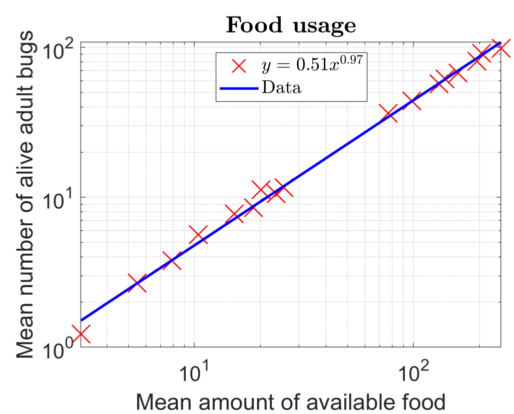

FIG. 6: Mean number of adult bugs depending on the mean amount of food available to the bugs at the start of each night for various simulations.

To explain this, the number of bugs and the number of adult bugs is plotted as a function of time in figure 7. It shows a clear periodic behaviour. This is caused by the fact that each bug can have hundreds of offspring. Therefore, when the bugs start reproducing, their number quickly becomes unsustainable, and most of them starve. This also explains why the previously mentioned coefficient is only 0.51 - much of the food is eaten by nymphs which starve before they become adults, and therefore that part of the food does not contribute to the number of adult bugs. In figure 6, the number of adult bugs peaks at about 250, while the mean available amount of food per night is about 100; this is caused by the fact that the bugs can go hungry for about a month before they die, so the number of bugs can 'buffer up'.

FIG. 7: Number of bugs and adult bugs throughout a simulation with on average around 200 food units available to the bugs at the start of each night.

B. Bug Intervention Results

Based on the effective model described above, several bug control techniques are integrated. The one evaluated in the model is pesticide by changing two parameters respectively.

The first one is the probability that a human sprays the pesticide when it noticed one bug (abbreviated as 'spray-notice ratio'). Compared with the mean number of adult bugs under the condition that the human will never spray the pesticide, even if the human only sprays once during the two-year simulation, the mean number of adult bugs decreases.

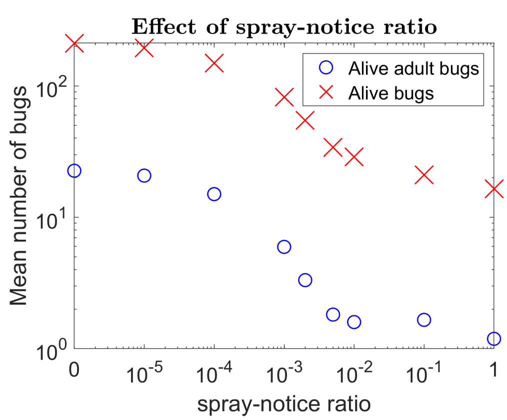

FIG. 8: Mean number of bugs and adult bugs depending on the probability that a human sprays the pesticide when it noticed one bug.

The mean number of adult bugs is plotted as a function of 'spray-notice ratio' in figure 8, showing a piece-wise relationship. When the spray-notice ratio is in the interval $(0, 0.01)$, the mean number of adult bugs monotonously decreases with the ratio increasing. However, if the ratio is larger than 0.01, the mean number of adult bugs will keep constant at 1 with small fluctuations.

The mean number of bugs, including the adults and the nymphs, is also plotted as a function of 'spray-notice ratio', showing a similarly changing pattern.

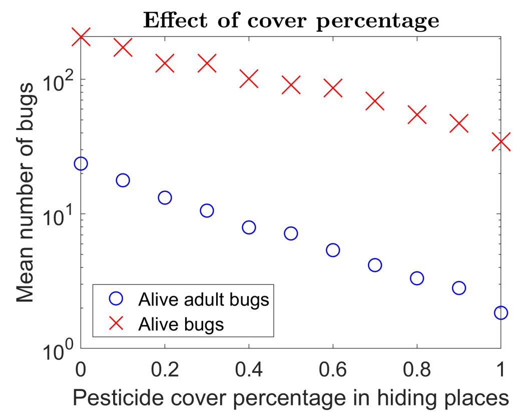

FIG. 9: Mean number of bugs and adult bugs depending on the probability that the coordinate point in the hiding place can be covered by the pesticide particle.

The second parameter is the probability that the coordinate point in the hiding place can be covered by the pesticide particle (abbreviated as 'p_{cover}'). In the above-mentioned analysis, p_{cover} is fixed as 0.8. In the following analysis, the mean number of adult bugs and the mean number of bugs are plotted as a function of p_{cover} in figure 9 with the 'spray-notice ratio' fixed as 0.002. The mean number of adult bugs and bugs both decrease exponentially fast with the increase of p_{cover}. Thus, the threshold of the pesticide effectiveness, to some extent, depends on whether a human pays enough attention on the hiding places.

These results show that spraying pesticide is an effective technique to control the bug infestation, and the more probably a human sprays pesticide when it noticed the bug, the fewer bugs are able to be alive. However, this technique has a certain threshold. Even if both of the two parameters are set as 1, i.e. the human will definitely spray pesticide once it notices one bug and the pesticide particles cover all the hiding places in the current room, the mean number of adult bugs is 0.75, and the mean number of bugs is 11.86. The reason is that the bugs are resistant to the drug to some extent; in the simulation the drug resistance is set as 0.2. So even all of the bugs are sprayed with pesticide, a few of them are able to survive. Thus, it is not enough to only use the pesticide as bug intervention.

IV. CONCLUSIONS AND OUTLOOK

To conclude, the model behaves as expected, and the results can be readily explained based on the assumptions. However, there are still some drawbacks in the current model and more work should be implemented in the future.

A. Drawbacks

Without real-world data, the question of realism cannot be definitely answered, as there is nothing to compare the model with. However, in case there are unrealistic elements in the model, its highly parametric nature means that they can most likely be easily remedied by small tweaks.

The bug model was designed with some simplifications which are not fully realistic. Because of the 10 minute time step, the bug does not actually move through the house, but instead it teleports to food, hiding places or other rooms. This is a simplification that leads to some assumptions that at first glance seem unrealistic, such as the fact that every bug knows the location of every food object in the room, or that bugs can move through rooms with humans without interacting with them[1]. However, it was deemed that 10 minutes are enough for a cockroach to search through a whole room and find food wherever it is. Furthermore, in the real world humans are usually focused on their current activity, so it seems feasible that bugs can move through rooms undetected, and even if not, the bugs mainly move at night when the humans are sleeping.

Another drawback of the bug model is the fact that there is no change in the behaviour of the bug as it grows older (except for the fact that it gets hungry slower). However, the main focus of the behaviour of the bug is finding food, and older bugs are updated before younger ones in each time step, so older bugs will naturally have priority when it comes to eating, but in a more realistic model this should most likely be a more qualitative difference.

Regarding drawbacks of the human model, it is important to know that it was created with a few assumptions. For instance, the humans eat breakfast and go to work at the same time each day. Also, they have a strict sleeping schedule of eight hours of sleep per night. These assumptions are a simplification of real-world human behaviour and are therefore to be considered as a drawback. More irregular behaviour of the human would lead to a more realistic model but it was not reasonable to do so during this project's time period.

[1] For example, a bug could move from the kitchen to the hallway without interacting with a human in the living area in figure 2.

B. Future Work

First, the basic model should either be compared against real world data or evaluated by a bug control expert to confirm its realism.

Second, a graphical user interface should be created to make it accessible to a broader audience.

Third, since almost everything in it is parametrized, parameters should be changed in different ways to check how this model works in different environments.

Fourth, more bug control methods should be implemented. For example, there is a novel bug trap, named 'Cockroach House'. The roach bait in the 'Cockroach House' has the same attraction as food to the bug. Once the bug eats the bait, it will not die immediately, but will be infected with the toxin and will die in a certain time period. If the bug goes back to the hiding places and dies, other bugs will eat its remains and will also be infected with the toxin. Thus, it is an effective method to clean the bugs in the hiding places. Also the effect of the combination of various bug control techniques should be evaluated to see the synergistic effect.

Fifth, the bug behaviour and human behaviour are based on limited data supplemented by the real-life experience of the authors, not on an accepted theory. And in this agent-based model, all the agents are considered independently. To adjust the model to be more realistic, the interaction between different bugs, the mutation in bugs, the interaction between different humans and some sudden actions should also be included.

Sixth, the idea of creating two humans and two bedrooms was first intended to see if it was possible to find a correlation between different behaviours of the humans. For example, if one human were meticulous with cleaning their bedroom and the other human was not, would this lead to some interesting results? This is something that a future project could work further on.

V. CONTRIBUTIONS

Contributions to the report were as follows:

- Joakim was responsible for chapter I, the introduction to chapter II, chapter IIB, chapter IVA.
- David was responsible for chapter IIA, chapter IIIA, the introduction to chapter IV, chapter IVA, chapter IVB.
- Ruxin was responsible for chapter IIA, chapter IIC, chapter IID, chapter IIIB, chapter IVB.

Contributions to the code:

- Joakim's focus was on creating the human behaviour and designing the house.

- David has been involved in almost every part of the code and he has also created the statistics.

- Ruxin has mainly worked with creating the bugs, the bug behaviour and the creation and evaluation of pesticide.

Appendix A: Code

The code for the project can be found in the GitHub project https://github.com/dtonderski/FFR120-project. The main program is in a MATLAB M-file named main.m. This program, will, in turn, make use of several classes described before.

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